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Fiber Bragg grating sensors - based mechanical structure damage identification

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1. Introduction

Localized damages to a mechanical structure affect the structural safety, reliability and operational life. Therefore the prediction, detection and monitoring of damages in structures has been the subject of intensive investigation. Displacement - related indexes (natural frequency or mode shapes) are not sensitive to local damage because they reflect structural global changes. Localized damage always contributes to stress/strain concentration around the damage areas according to the Theory of Elastic Mechanics, hence the strain - related damage identification methods have received more and more attention for decades [1-4]. Yam et al. [5, 6] have given some comparative sensitivity analysis of several strain - related damage identification indicators, the results of their works shows that strain frequency response function (SFRF) index is the simplest and most effective one and easy to be realized in practical applications.

Local damage is tiny and in unknown location. Therefore, the prerequisite of successful damage identification by strain - related index depends on accurate measurements of strain field in structure, which requires strain transducers extensively used. However, traditional strain gage has a problem of trivial wiring, and electric transducer is vulnerable to electromagnetic interference. Capoluongo et al. [7] demonstrates the capability of modal analysis and damage detection by fiber Bragg grating (FBG) sensors, have tested and verified the superiority of FBG sensor's application in structural health monitoring over other transducers (strain gage and accelerometer). The most advantages of FBG sensors are reduced dimensions combined with the intrinsic capability to measure several parameters simultaneously; the high resistance to corrosion and fatigue, good compatibility with most advanced composite materials exploited in the aeronautic and aerospace field, immunity to electromagnetic interference, the wide bandwidth operation and an excellent multiplexing capability. These characteristics make FBG sensors easy to carry out distributed sensing network strain field measurements in mechanical structures.

In this work, a SFRF - based index adapted to FBG distributed strain field measurement is proposed. Then finite element numerical analysis and experimental tests are implemented to verify the feasibility of this damage index.

2. Damage identification index based on SFRF

Since frequency response function parameter can provide much more information on the desired frequency range than modal data, and SFRFs are verified as effective for estimation of damage location and severity in structure. Initially, the strain frequency response function H^{ε} at point *i* due to the excitation *j* can be expressed as

$$H_{ij}^{\varepsilon}(\omega) = \psi_i^{\varepsilon} \Lambda^{-1} \Phi_j \tag{1}$$

where ψ_i^{ε}, Λ^{-1}, Φ_j are the *i*-th row of the strain mode shape matrix, the displacement transfer function and the *j*-th column of the displacement mode shape matrix, respectively. Yam, Li and Wong [5] have given the SFRF index with the consideration of damage severity which can be expressed as

$$\beta(\alpha) = \sqrt{\frac{1}{L}\sum_{k=1}^{L}\left(\sum_{i=r_1}^{r_n}\left[\tilde{H}_{ij}^{\varepsilon}(\alpha,\tilde{\omega}_k) - H_{ij}^{\varepsilon}(\alpha,\omega_k)\right] \Big/ \max_{I\subset[1,m]}\left\{\sum_{i=I_1}^{I_n} H_{ij}^{\varepsilon}(\alpha,\omega_k)\right\}\right)^2} \tag{2}$$

where α is a value of damage severity, ω_k and $\tilde{\omega}_k$ are the natural frequency respectively for the intact and defective case, H_{ij}^{ε} and $\tilde{H}_{ij}^{\varepsilon}$ are respectively strain frequency response function between points *i* and *j* of the intact structure and the damaged case. *L* is the number of frequencies in the desired frequency range, and r_n is the number of nodes in one element.

For a certain α, damage location can be identified from the peaks of $\beta(\alpha)$. For α varying, $\beta(\alpha)$ is a function of α at the detective area. Yam investigated the sensitivity of that index through numerical analysis, no experiment tests according to which were given. In Yam's method, the frequency response function of each node in each element must be calculated, that is not suitable for practical test. Hence, in this work another similar form index is given for the strain measurement by FBG sensing

$$\beta_{sfrf} = \sqrt{\frac{1}{L}\sum_{k=1}^{L}\left(\left[\tilde{H}_{ij}^{\varepsilon}\left(\alpha,\tilde{\omega}_k\right) - H_{ij}^{\varepsilon}\left(\alpha,\omega_k\right)\right] / max\left[H_{ij}^{\varepsilon}\left(\alpha,\omega_k\right)\right]\right)^2} \tag{3}$$

3. FBG distributed sensing

The principle of FBG sensing is the changes of strain, temperature or other physical quantity around gratings make grating cycle or the refractive index of fiber core variation, consequently the wavelength of grating's Bragg signal shifts. So any change of the physical quantity can be obtained from the shift of FBG wavelength.

The variation of the grating cycle Λ or the effective refractive index of fiber core n_{eff} can lead to the shift of FBG Bragg wavelength. Their relationship can be expressed as

$$\lambda_B = 2n_{eff}\Lambda \tag{4}$$

By neglecting the temperature effect, the shift of Bragg wavelength caused by the change of stress or strain can be written as

$$\Delta\lambda_\varepsilon = \left(1 - p_e\right)\varepsilon\,\lambda_B = K\varepsilon\,\lambda_B \tag{5}$$

where p_e is elastic - optic coefficient, λ_B is the wavelength without strain affecting, ε is the axial strain, K is relative strain sensitivity coefficient of FBG, $\Delta\lambda_\varepsilon$ is the strain change caused by the wavelength shift. Usually, K is a constant value when the material of FBG is selected. For example, K of molten quartz fiber material is 0.784, if wavelength of grating is 1.312 μm, by Eq. (5) the wave - length shift caused by the unit axial strain of FBG is 1.03 pm.

In this work wavelength division multiplexing technique has been adopted for FBG distributed sensing. A schematic illustration for FBG distributed sensing measuring system is shown in Fig. 1. From this picture, in an optic fiber FBG sensors with different Bragg wave - length are connected one by one, broadband light source is emitted from a super light emitting diodes (SLED) system to a coupler, then to FBG sensors, and each grating reflects a narrowband light wave back with unique Bragg wavelength. From the reflected light, the wavelength shift quantity of each grating can be detected by wavelength demodulation system. According Eq. (5), the strain at each grating can be acquired from wavelength shift quantity every point. Then the strain field along this fiber can be obtained from the wavelength shift of gratings.

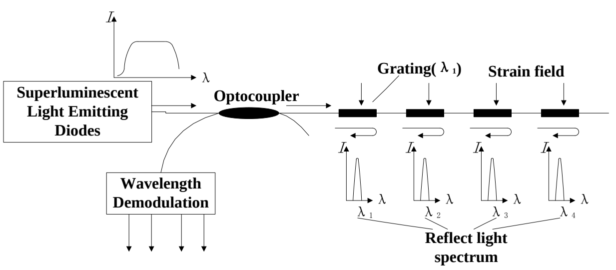

Fig. 1 The FBG distributed sensing system by wavelength demodulation

4. Numerical analysis

In many areas of engineering applications such as aerospace, automotive, civil and mechanical engineering, plate - like structures are widely used as an important structural component. Consider a simply supported plate ($a \times b \times h$, divided into 100 rectangular elements) with defective areas occurring at the surface as shown in Fig. 2. The structure for numerical analyses is the same as experiment test samples, and four - corner are all constrained. And defect is simulated by reducing the thickness of the damage areas shown in Fig. 2. The dimensions of the plate and the defective area are 500 × 500 × 3 mm and 50 × 50 × h_c mm, (h_c is the thickness of damaged area), respectively. A sine force $F = 100\, sin\,(\omega t + \pi / 4)$ N is imposed on the geometric center of the plate as exciting force. The x - direction strain of each point (where marks "×") in the plate in frequency domain are acquired for the intact and damaged conditions, and the difference between these cases is calculated and processed using the finite element analysis by commercial soft - ANSYS.

For an illustration of sensitivity estimation using the SFRF index β_{sfrf}, assume that only one damage occurring at area A1 with the reduction of thickness (Fig. 2). The numerical analysis results show that almost no change to the natural frequency after damaged (for an example, the 1-st natural frequency shifts from 50.302 Hz to 50.286 Hz). The SFRF amplitude of 1-st natural frequency shows little change, the 2-st one is taken for analysis. Set the reduction thickness of area A1 to be 0.1 mm, and consider the frequency range from 144 Hz to 184 Hz, the β_{sfrf} index of every point marked can be calculated using Eq. (3), then the results are plotted in Fig. 3.

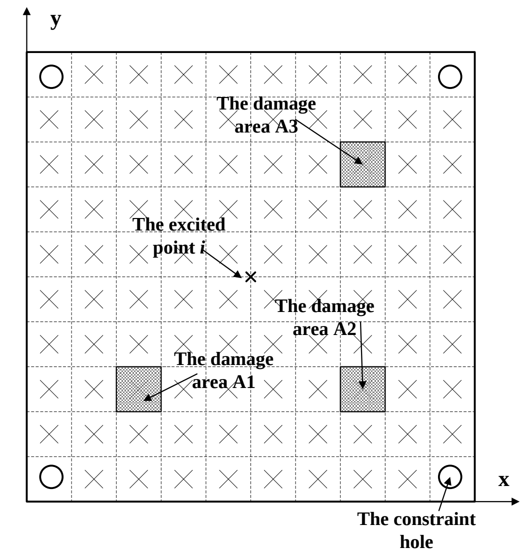

Fig. 2 Finite element model of the plate with damage

One significant peak at A1 is observed form Fig. 3, and the sensitivity of the SFRF to damage is confirmed by the accurate identification of damage location. To illustrate severity estimation performance of the SFRF index, the structure with single damage at A1 with depth changing from 0.3 mm, 1 mm, 2 mm to 2.5 mm is taken for analysis, the values of β_{sfrf} index for these four cases are 3.011, 3.801, 5.512 and 8.134. With quartic curve fitting, the tendency of β_{sfrf} vs the severity of damage is plotted in Fig. 4, based on the curve the severity can be estimated from the figure by taking a value of β_{sfrf} index.

For simulating multi - damage states, the other two cases are set, there are two damaged areas at A1 and A2 that is one case, and three damaged areas appear at A1, A2 and A3 that is the other case. The results of the two cases are plotted in Fig. 5, which shows that the SFRF index can also be adequate to identify multi - damages.

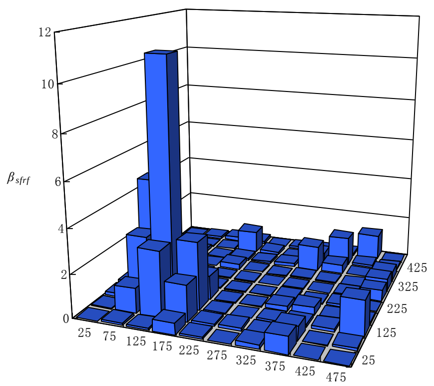

Fig. 3 Histogram of β_{sfrf} index with single damage (0.1 mm thickness reduction)

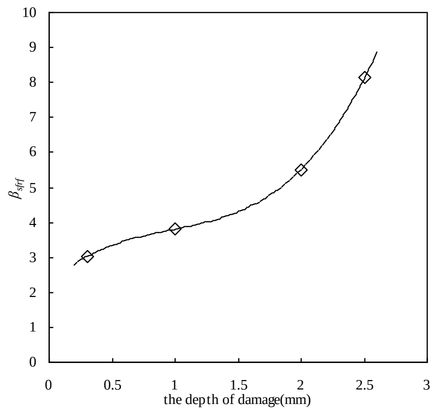

Fig. 4 β_{sfrf} index vs the severity of damage

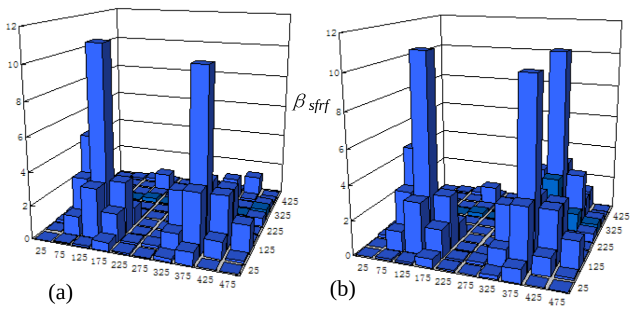

Fig. 5 The SFRF index for a structure (a) two damaged areas; (b) three damaged areas

5. Experimental test

In order to verify the effectiveness of the SFRF index for the damage identification, experimental tests using steel plate was conducted. The structure is the same as the model in Fig. 2. The intact plate was firstly tested, then the damaged one with a hole milled in the location of L3 in Fig. 7, the diameter of the hole is 20 mm. Fig. 6 shows the experimental setup used for testing. A sinusoidal signal was generated and amplified by a vibration analyzer system (B&K 7700 PULSE), then drive a modal exciter (B&K 4824), and a force was imposed vertically on the center of the plate. An optic fiber grating signal demodulation device (MOI Sm130-700) was taken for FBG signal acquisition. The strain responses in x direction were sensed by seven FBG sensors naked adhered on the plate (three at L1, L2 and L3, three at L4, L5 and L7, and one at L6 in Fig. 7).

Fig. 6 Experimental setup

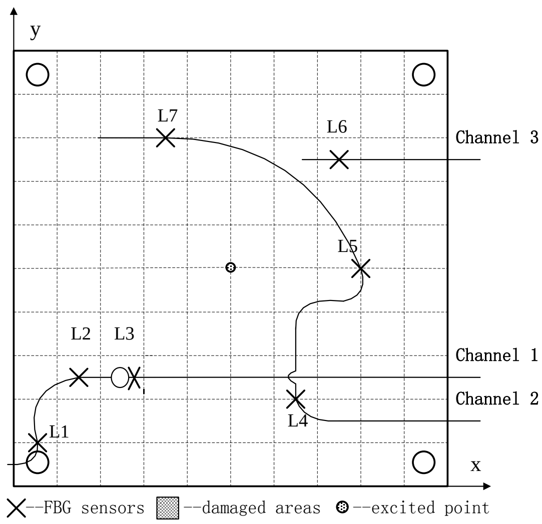

Fig. 7 Arrangement of FBG sensors

The plate was excited by harmonic sweep frequency force, for example, when 10 N harmonic force of 60 Hz was use, the FBG response in time - domain is shown in Fig. 8. The SFRF amplitude of 60 Hz can be obtained by calculating the ratio between the peak values of Fourier form of the wavelength response and the time domain force, similarly other SFRF amplitudes in the sweep frequency range can be obtained, connecting all the SFRF amplitude points into line makes the strain frequency response function curve.

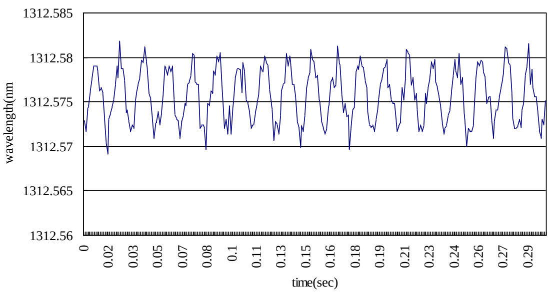

Fig. 8 Wavelength response in time - domain

The SFRF curves received from FBG at L3 was plotted in Fig. 9 from 68 Hz to 110 Hz, among which there is a natural frequency 78 Hz (the intact case), the natural frequency of damage case (85 Hz) shifted for nearly 5 Hz, the reason must be the irreversible changes caused by the milling process for damage simulation. Substituting the SFRF of intact and damaged structures into Eq. (3) consider SFRF index value of the point considered.

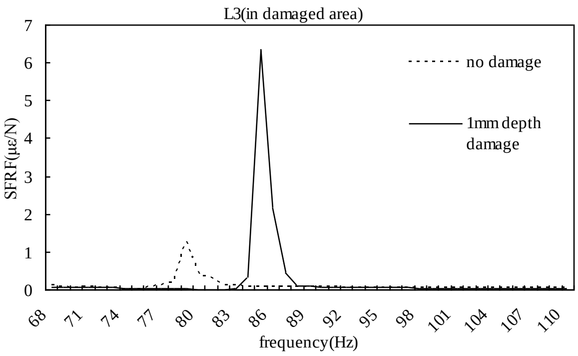

Fig. 9 SFRF curve in L3 by experimental tests

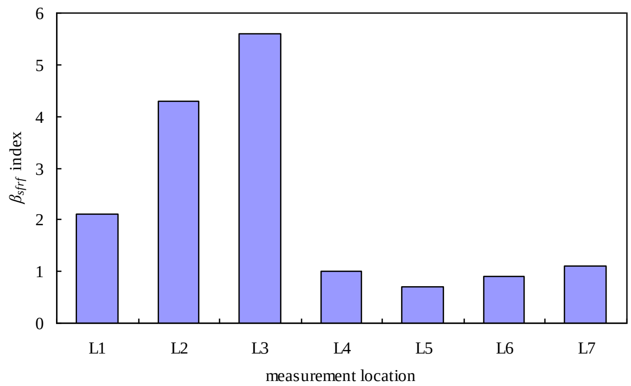

Fig. 10 The SFRF index of measurement locations

Fig. 10 shows the histogram of SFRF index at measuring locations. The SFRF index β_{sfrf} achieves its maximum at L3 which is the damage location. Peaks of β_{sfrf} also appear at locations L1 and L2, the reason were that they were close to the damaged area. From the discussion above, obviously, β_{sfrf} index is a sensitive parameter for damage location identification. And the strain field can be well measured by FBG distributed sensing network.

6. Conclusion

1. FBG distributed sensing is suggested to apply to strain field measurement of mechanical structure. Experimental tests results show that this technique is convenient and effective for mechanical structural health monitoring.

2. Based on strain frequency response function, a damage identification index β_{sfrf} adapted to FBG strain sensing is proposed.

3. From numerical analysis results, the proposed β_{sfrf} index is quite sensitive to local damage, and can discern multi - damage in one structure. Also, the relationship curves between the damage severity and the SFRF index can be used for damage severity determination.

4. From the results of β_{sfrf} index calculated from SFRF of measurement points, it is verified that the index β_{sfrf} is an accurate and effective damage identification indicator for practical application.

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References

1. **Li, Y.Y.** 2010**.** Hypersensitivity of strain - based indicators for structural damage identification: A review, Mechanical Systems and Signal Processing, 24: 653-664. http://dx.doi.org/10.1016/j.ymssp.2009.11.002
2. **Chen, G.; Mu, H.M.; Pommerenke, D.** 2004. Damage detection of reinforced concrete beams with novel distributed crack/strain sensors, Structural Health Monitoring 3: 225-243. http://dx.doi.org/10.1177/1475921704045625
3. **Lee, J.W.; Kirikera, G.R.; Kang, I.** 2006. Structural health monitoring using continuous sensors and neural network analysis, Smart Materials and Structures 15: 1266-1274. http://dx.doi.org/10.1088/0964-1726/15/5/016
4. **Swadimas, A.S.J.; Chen, Y.** 1995. Monitoring crack growth through change of modal parameters, Journal of Sound and Vibration 186: 325-343. http://dx.doi.org/10.1006/jsvi.1995.0452
5. **Li, Y.Y.; Cheng, L.; Yam, L.H.** 2002. Identification of damage locations for plate - like structures using damage sensitive indices: strain modal approach, Computers and Structures 80: 1881-1894. http://dx.doi.org/10.1016/S0045-7949(02)00209-2
6. **Yam, L.H.; Li, Y.Y.; Wong, W.O.** 2002. Sensitivity studies of parameters for damage detection of plate - like structures using static and dynamic approaches, Engineering Structures 24: 1465-1475. http://dx.doi.org/10.1016/S0141-0296(02)00094-9
7. **Capoluongo, P.; Ambrosino, C.; Campopiano**, **S.** 2007. Modal analysis and damage detection by Fiber Bragg grating sensors, Sensors and Actuators A133: 415-424. http://dx.doi.org/10.1016/j.sna.2006.04.018

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PLUOŠTINIS TINKLINIS BRAGGO JUTIKLIS MECHANINIŲ KONSTRUKCIJŲ PAŽEIDIMO VIETOS NUSTATYMUI

R e z i u m ė

Straipsnyje aprašomas metodas dviejų matmenų plokščių konstrukcijų pažeidimo vietai aptikti. Pažeidimo indekso nustatymui šiuo metodu matuojama deformacijos dažnio reakcijai nepažeistai ir pažeistai vietai. Deformacijos dažnio funkcija matuojama išskirstytu pluoštiniu tinkliniu Brago jutikliu. Atlikti imitavimo ir eksperimentiniai tyrimai. Abiejų tyrimų rezultatai rodo, kad šiuo metodu jungiant deformacijos dažnio reakcijos funkciją ir išskirstyto pluoštinio Brago tinklinio jutiklio duomenis galima sėkmingai nustatyti pažeidimo vietą.

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FIBER BRAGG GRATING SENSORS - BASED MECHANICAL STRUCTURE DAMAGE IDENTIFICATION

S u m m a r y

This paper describes a method for identifying the damage location for two dimensional plate - like structures. This method uses measured strain frequency response functions from intact and damage state to define a damage identification index. The strain frequency response functions are measured by distributed fiber Bragg grating (FBG) sensors. Numerical simulation and experimental tests are carried out. Both results show that this method combining strain frequency response function - based index with FBG distributed sensing can successfully identify the damage location.

Keywords: fiber Bragg grating sensors, mechanical structure damage identification.

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